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A COMPREHENSIVE STUDY OF GLASS FIBRE REINFORCED POLYMER (GFRP) DRILLING

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ABSTRACT

Machining is one of the most common subtraction manufacturing process, wherein the final shape of the product is obtained by removing of excess material from the work part. The rising demand for high performance structural material necessitated the development of composite materials and like any other engineering material, to be a part of final assembly, the composites are also required to undergo the machining processes. The most common machining operation is the mechanism of making hole, known as drilling. The drilling of fibre reinforced polymers (FRPs) distinctively differs from that of the drilling mechanism in conventional metals, due to the prior's inhomogeneous nature. The machining quality for drilling composites is quantified through surface roughness (surface morphological issue) and the delamination (surface integrity issue). The article presents a comprehensive analysis of the effect of various parameters viz. drill tool material and drill process parameters on the said machining quality factors, whilst drilling of glass fibre reinforced polymer matrix composites.

***KEYWORDS:** Fibre Reinforced Polymers, Composite Drilling, Machining Quality & Delamination Damage Factor*

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Original Article

1. INTRODUCTION

Machining could be defined as a sub- traction manufacturing process, used to remove material controllably from a weak material, with a main objective of producing the final product with the appropriate shape. Any machining takes place due to the relative motion between the work part and tool, however there are several other factors' viz., tool material, and work piece material, process parameters that affects the machining process(Saleh & Bahar, 2017). Any machining mechanics deals with the determination of cutting force and cutting power (thrust force and torque) through evaluating the thermo-mechanical processes involved during material removal (Astakhov & Outeiro, 2008). Turning, drilling, milling, etc. are certain types of conventional machining processes whereas electro-discharge machining, abrasive jet machining, etc. are they types of available non-conventional machining processes.

1.1. Fibre Reinforced Polymer Machining

The machining of fibre reinforced polymers (FRP) laminates, are distinct in nature, when compared to the machining of the metals, as the prior are inhomogeneous engineering materials comprising distinctly different phases viz., reinforcement phase and matrix phase. The machining of FRPs is characterized by intermittent fracture and the machinability of the laminates and is principally determined by the mechanical and physical properties of matrix and fibre materials, fibre content and fibreorientation, unlike the metals, wherein the characterization is

based on the shearing and plastic deformation causing the chip formation. Since the matrix strength, is normally mediocre to that of the fibres, the cutting forces are majorly dependent on the latter. Whilst the glass and carbon fibre breaks and showcases to be brittle in nature during the machining, the aramid fibres have a tendency to bend ahead of the progressing cutting edge. Apart from the cutting forces, the cutting temperature is also affected by the thermal proper- ties and orientation of the fibres in the laminate. Carbon fibres being comparably good conductor of heat than the glass and aramid fibres, shows the capability of dissipating heat in a better manner form the cutting zone. However, the FRP laminates are not meant to be machined at high temperatures like in the case of metals and precautions must be taken, not to expose the matrix to excessive heat for a prolonged time. In addition, the difference in the thermal expansion of fibre and matrix material gives rise to the major concern of deformation and work-part damage (Sheikh-Ahmad, 2009).

1.2. Machining Quality

The quality of machining is a function of surface morphology and integrity. The prior is related to the geometrical features of the machined surface and function of tool geometry, material, tool rigidity and kinematics of the machining process. The latter deals with the chemical and physical changes of the work – part surface layer after machining. Both the said functions of machining quality relies on the tool material, work material and process parameters.

The machining quality is a significant factor as in a long run, it affects the strength and chemical resistance of the final component, hence, necessitates the need of characterizing and quantifying the quality of machined surfaces. Surface rough- ness (Ra) is generally used to describe the surface morphology whereas the measurement of delamination, fibre pullout, etc. are used to quantify the surface integrity (Sheikh-Ahmad, 2009)

1.3. Machining Issues in FRP

The following issues represent major concerns while machining fibre reinforced polymer composites (König, Wulf, Graß, & Willerscheid, 1985):

- Local dynamic loading tend to result in the physical de- lamination, especially in the glass and aramid FRPs due to the difference in the stiffness of the matrix and fibre element.
- The difference in the thermal expansion coefficient of the fibre and matrix material tends to cause the thermal de- lamination.
- The low flexural strength, particularly in carbon fibres, cause spalling (breaking) of fibres.
- Fuzz comprising pulled out and crushed fibres occurs in case of FRPs, if the tensile strength is low for the laminate.
- The poor thermal conductivity of the matrix materials limits the usage of high temperature machining and hence the machining must be done with high power density and short interaction time.
- Machining parameters if not adjusted or optimized, can result in severe damage in the work material and tool material.

1.4. Drilling of Composites

Drilling is a conventional hole making process which marks to be one of the most common machining operation (secondary machining). It is used mainly to facilitate the fastening in mechanical parts and structures. Though, drilling is

conventionally done using a twist drill, there also exists non-conventional machining process like laser beam drilling (LBD), water-jet drilling (WBD) etc., to be used for the same purpose. The machining quality in drilling depends upon the process parameters viz., cutting speed and feed, tool materials, work-piece materials and tool-wear rate (TWR) (Paulo, 2018).

In a conventional drill, the conical twist drill with two flutes is used, as represented in the Figure 1. The tool has three discrete types of cutting surfaces, viz., two marginal cutting edges, two main cutting edges and a chisel edge.The point angle generally preferred for metals is 118° whereas it is around 135° for FRP. The drill suitably ground to the mentioned angle gives the satisfactory results for a wide range of materials. The point angle can be reduced with the increase in the brittleness of the material (Krishnaraj, Zitoune, & Davim, 2013).

1.4.1. Drilling of FRP Composites

The increasing demand of high- performance engineering materials in various industries, led to the development of fibre reinforced polymer composites. Amongst the available choices, the most widely used composites in the industries are the glass fibre reinforced polymer (GFRP) and the carbon fibre reinforced polymer (CFRP) laminates. Due to their strength–to–weight and stiffness–to–weight ratio, the said laminates have been finding high rate of applications as the structural materials in several industrial sectors viz., aerospace, marine, etc. As structural materials, the joining of the laminates to each other or to other material structures becomes necessary and the only way of accomplishing this by fastening them mechanically. The efficiency of the thus said joining method depends on the quality of drilled holes (Liu, Tang, & Cong, 2012)

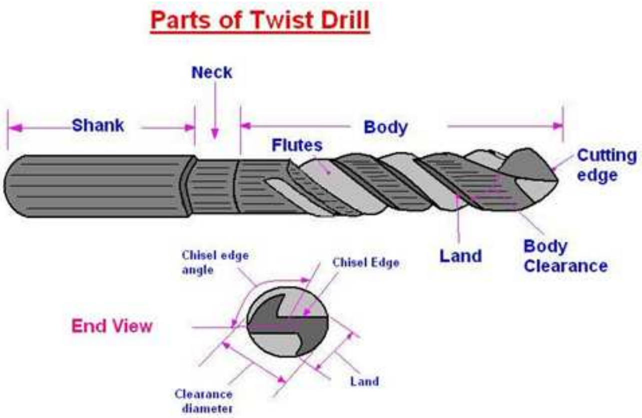

Figure 1: Nomenclature of a Standard Twist Drill

1.4.2. Machining Quality in Drilling of FRPs

As mentioned earlier in this article, the machining quality is a function of surface integrity and surface morphology. The following sub-section deals with each of the said elements in detail. Surface integrity issues with drilling of FRPs: The principal damage or in other words the highly undesirable problem that has been recognized in the drilling of composites is the delamination (an inter-ply failure phenomenon). The de- lamination reduces drastically the assembly tolerance and in addition, has the potential for long-term-performance deterioration. Various experimental observations have proved that the drilling induced delamination could be classified as peel- up, push-down and wall delamination (explained in detail in the following subsections of this article), on the basis of their existence. The peel up delamination occurs around the entry periphery of the drilled holes whereas, the push down occurs at the tool exit periphery(Krishnaraj

et al., 2013; Liu et al., 2012)

- **Peel-Up Delamination**

Figure 2 represents the peel-up delamination mechanism. It follows as the drill tool enters the laminate. Once the cutting edge of the drill establishes contact with the laminate surface, the cutting force (thrust force) acting in the peripheral direction causes the delamination by generating a peeling force in the axial direction through the slope of the drill flute. The said mechanism results in the separation of the laminas from each other forming delamination zone at the laminates top surface(Khashaba, 2004).

- **Push-Down Delamination**

The push-down or push-out delamination damage mechanism befalls as the drill tool reaches the exit side of the work part and is as represented in Figure 2. When the drill tool approaches the end, the uncut thickness reduces in turn reducing the resistance to the deformation. Since the loading exceeds the interlaminar bond strength, the delamination occurs. The said mechanism occurs before the laminate is completely drilled (Khashaba, 2004).

- **Delamination Assessment**

There exists various method of observing the delamination effect viz., optical microscope, stereomicroscope, ultrasonic C – scan, digital photography technique, shadowMoire laser based imaging technique, X-ray computerized tomography, etc. Figure 3 represents the delamination observed in FRPs using scanning electron microscope (Liu et al., 2012).

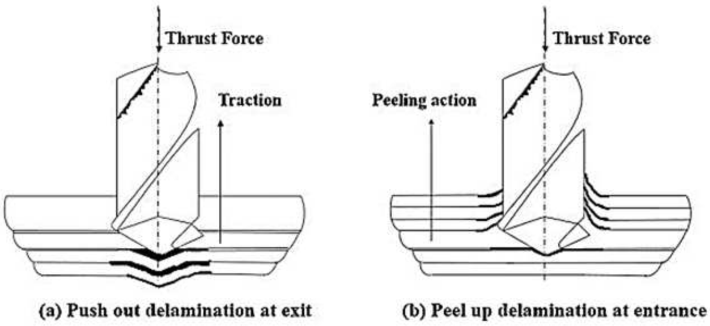

Figure 2: Delamination Mechanism in Composite Drilling

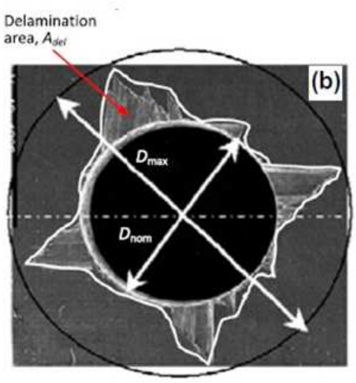

Figure 3: SEM Image of a Drilled FRP (Source: Rawat and Attia,2009)

Of the several methods of assessing the level of the delamination damage, the most commonly used is the one-dimensional factor (F_d), defined as, the ratio of the maximum diameter (D) of the detected delamination zone to the nominal diameter (d) of the drilled hole. The maximum diameter and the nominal diameter has been represented in Figure 3. Mathematically, it is

$$F_d = \frac{D}{d} \quad (1)$$

Since the degree of delamination caused by just a few fibres peeled up or pushed down to a significant width might not depict the real delaminated damage zone of the drilled hole periphery, Eq. (1) was modified to a two-dimensional delamination factor (Fa), which mathematically is given as (Faraz, Biermann, & Weinert, 2009).

$$F_a = \left\{\frac{A-a}{A}\right\}\% \quad (2)$$

Wherein, 'A' is the area of delamination damage area and 'a' represents the nominal area of the drilled hole. A correction factor was proposed by Davim and hence adjusted the Eq. (2) grounded on the digital image analysis to assess the delamination (F_{da}) after drilling as (J. Davim, Rubio, & Abrao, 2007)

$$F_{da} = \alpha\left(\frac{D}{d}\right) + \beta\left(\frac{A}{a}\right) \quad (3)$$

Wherein, the elements α & β were used as weights in the parts. Though the corrected equations exists, the one dimensional delamination factor, F_d is been used mostly in practice (Liu et al., 2012).

- **Surface Morphological Issues with Drilling of FRPs**

Surface roughness (R_a) depends critically on the fibre orientation. The surface morphology around the work material circumference depends on the angle between the cutting velocity vector and the fibres. It is evident from the Figure 4 that, as the circumferential angle (ϕ) increases from 0° to 180°, the fibre orientation angle (θ) reduces. Mathematically the reduction is represented as given in Equatoin (4).

$$\theta = 180° - \varphi \quad (4)$$

On further increasing the circumferential angle, the reduction of the fibre orientation angle follows the Equation (5).

$$\theta = 360° - \varphi \quad (5)$$

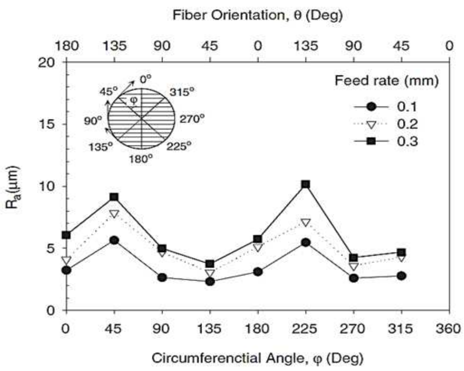

Figure 4: Surface Roughness Variation with Reference to the Circumferential Position

The surface roughness is observed to exhibit nearly a sine wave with maxima at circumferential angle, $\phi = 45°$ and 225° and lowest at $\phi = 135°$ and 315°. On calculating, using the equations 4 and 5, the results yield that the maximum surface roughness exist when the fibre orientation angle $\theta = 135°$ and is minimum when $\theta = 45°$(Sheikh-Ahmad, 2009). The article deals with the comprehensive study of the influence of various drilling process parameters, drill tool material and work material properties, whilst drilling of glass fibre reinforced polymer composites.

2. INFLUENCE OF DRILL PROCESS PARAMETER ON MACHINING QUALITY

Though there exists various process parameters in a machining process, the ones of concern, in particular to the drilling of composites are the cutting speed, feed, point angle and chisel edge width. This subsection of the article deals with the explorative investigation of the effect of the said process parameters on the machining quality of GFRP.

2.1 Influence of Drill Process Parameters on Delamination

Delamination induced during drilling is one serious problem/damage caused in the GFRP work material. The study conducted by the researchers (Kumar & Sing, 2017)using response surface method to conduct the design of experiment and one dimensional delamination factor equation to deter- mine the delamination effect, showed that the feed rate is the most significant factor with respect delamination and found the optimum speed and feed to be 2000 rpm (from a range of 500 to 2000 rpm) and 0.10 mm/ rev (from a range of 0.1 to 0.5 mm/rev) respectively. An experimental research was carried out by the researchers (Sunny, Babu, & Philip, 2014) to investigate the effect of drilling process parameters viz., cutting speed and feed on the delamination in drilling GFRP composite laminates. The work dealt with 5 levels each of feed (mm/min) ranging from 1000 to 3000 and speed (rpm) ranging from 50 to 400.

The Taguchi method was utilized to design the experiment and analysis of variance (ANOVA) was made use of to investigate the effect of the parameters. The damage around the drilled hole was measured using a pro- file projector with a magnification factor of 20x. The one dimensional delamination factor equation was used to calculate the damage.The result showed that the delamination factor decreased with the increase in spindle speed until the speed reached 3000 rpm, after which there was a steep rise. The rise in the delamination factor value at 3000 rpm was due to the softening of fibre and matrix, as the cutting temperature in- creases with the cutting speed. While observing the feed rate effect, delamination factor was found to be less within the range of 50 to 100 mm/min. The lowest delamination factor value was observed at a feed value of 50 mm/min and speed of 2500 rpm. Comparing the two parameters the results showed that the feed rate is more influential than the cutting speed with regards to the delamination factor.

The researchers (Velaga & Cadambi, 2017) investigated the effect of cutting speed and feed on the delamination caused in the work material during drilling of GFRP. The speed and feed each were chosen for three levels. The speed ranged between 400 to 1000 rpm and the feed ranged be- tween 0.2 to 0.6 mm/rev. Two dimensional delamination factor equation without Davim’s correction was used in the investigation and the same was validated using numerical simulation method. The experimental work resulted in determining the optimum speed to be 700 rpm at 0.4 mm/rev feed. In addition, the work also strongly validated the point that feed rate is the most significant factor in case of delamination as at varying feed rates for the same speed, the delamination effect was high.

Yet another point to be emphasized is that the rise in feed rate (increases the thrust force) significantly increased the delamination effect. The authors (Mohan, Kulkarni, & Ramachandra, 2007; Mohan, Ramachandra, & Kulkarni, 2005) in their comprehensive investigation, determined that drill process parameters viz., speed and feed affects the delamination

damage induced during the drilling of GFRP composites. The drill speed and feed chosen for the experiment ranged between 600 to 1500 rpm and 50 to 125 mm/min respectively. The experiment resulted in determining the optimum range of speed to be 600 to 1200 rpm and feed to be 50 mm/min in order to attain minimum delamination.

The authors (Zarif Karimi, Heidary, Fotouhi, & Minak, 2017) investigated the effect of cutting speed and feed on the delamination caused in the GFRP during drilling operation. The work involved 3 levels of each speed (315 to 1000 rpm) and feed (31.5 to 125 mm/min). The delamination factor was calculated using the Davim's adjusted two-dimensional delamination factor equation. It was found that the feed influenced the most. The optimum speed and feed to have minimized delamination was determined to be 1000 rpm and 31.5 mm/min respectively.

2.2. Influence of Drill Process Parameters on Surface Roughness

A research work conducted by the authors considered the effect of chisel edge width and point angle, in addition to the cutting speed and feed, on the delamination caused during drilling. Taguchi method was used to design the experiment and ANOVA was used to determine the effects of the parameters. The investigation dealt with 3 levels each of speed ranging from 500 to 1500 rpm, feed ranging from 10 to 90 mm/min, point angle ranging from 85 to 95° and the chisel edge width ranging from 0.8 to 1.6 mm. The surface roughness was measured using Surtronic 3+ Taylor Hobson Talysurf surface profolio meter. The experimental work resulted in determining the optimum parameters with regards to surface roughness of final product as speed of 500 rpm, feed rate of 20 mm/min, point angle of 95° and chisel edge width of 0.08 mm. In addition, it was also observed that the feed followed by speed are the most influencing factor and the chisel edge width is the least significant factor preceded by the point angle (Vankanti & Ganta, 2014).

A detailed investigation lead by authors (El-Sonbaty, Khashaba, & Machaly, 2004) has experimentally validated the fact that the cutting speed has insignificant effect on the surface roughness, whereas the feed is the most influencing parameter to be considered in order to control the sur- face roughness while drilling GFRP. It was observed that the lower feed deliver increased roughness compared to drilling at higher feed.

3. INFLUENCE OF DRILL BIT ON MACHINING QUALITY

Though there exists fewer articles proving the effect of drill bit on delamination, the one that are present are sufficientto understand the influencing effect. The drill type has a significant effect on the delamination caused during drilling of the GFRP composites. The researchers (Hocheng & Tsao, 2003)in their work validated the said fact by analysing the effect of various drill bit types and comparing the same with the conventional twist drill bit.

The authors (Abrão, Rubio, Faria, & Davim, 2008; J. P. Davim, Reis, & António, 2004)also in their work very well validated the fact that the difference in the drill bit geometry and type has an appreciable effect on the delamination caused during drilling of GFRP laminates. The experimental work undertaken by the researchers (Sunny et al., 2014)used three types of drilling tools viz., twist drill, end mill and Kevlar drill. Figure 4 represents the said drill tools.The experiment depicted that for a given value of the cutting speed, the usage of twist drill showcases the maximum delamination factor and the minimum delamination factor was obtained by using the Kevlar drill.

A detailed investigation by the authors (Kumar & Sing, 2017)based on the effect of drill tool materials on the delamination, showed that the solid carbide drill induces the minimal delamination damage compared to conventional high-speed steel (HSS) drill and the carbide tipped K20 drill. An experimental work by the researchers (Liu et al.,

2012)showed that it is not just the type of drill that matters in case of delamination but the right geometry. The experiment made use of three candle-stick drills of varying drill-tip geometry and compared the delamination effect on GFRP laminates with respect to conventional twist drill. The experiment resulted in proving that not all the prior mentioned drill bits exhibit to be better than the twist drill. The drill-bit geometry was optimized to achieve excellent drilling result.

An experimental investigation has shown that the tool material used for drilling of GFRP laminates hold utmost importance. The work by the authors (Arul, Vijayaraghavan, Malhotra, & Krishnamurthy, 2006) show that for a tipped carbide tool, the tool wear rate is comparably lower than the HSS and tin coated HSS tool. The increase in the wear of the tool, increases the thrust force, which in turn increases the delamination damage in the work material. The work showed that the delamination damage caused by the tipped, carbide tool while drilling the 50th hole was equivalent to the 30th hole drilled by tin coated HSS.

4. CONCLUSIONS

From the literature reviewed, the following points are quite evident

- Drilling is not only one of the most used secondary machining process, but is an essential process to be carried out, particularly in composites for joining the parts, in order to complete the assembly.
- Drilling of composites vary distinctively from that of the conventional metals as in case of composites the chip forming mechanism does not govern principally the process.
- Drilling inappropriately causes damage in the machined quality, viz., surface integrity and surface morphology.
- The principal damage in terms of surface integrity is the delamination (pee-up, push-down and wall delamination), which not only affects the assembly tolerance but also significantly affects the load-carrying capacity of the final product.
- The machining quality in terms of surface morphology is quantified through the surface roughness of the final machined product.
- The cutting forces and power (thrust force and torque) are highly affected by the various process parameters, which in turn influences the delamination and surface roughness.
- The delamination is quantified by the term delamination factor, which could be determined either by onedimensional delamination factor equation (most widely used) or by two-dimensional delamination factor equation (with or without Davim’s adjustment factor).
- It is found that feed rate is the most influencing process parameters of all, both with respect to delamination and surface roughness.
- Though the chisel edge width is one of the process parameters in drilling, it has the least influence over delamination and surface roughness.
- Using the conventional drilling process, the optimum speed of drilling obtained could be summarized to range between 600 and 2000 rpm, beyond which the cutting temperature increases and may increase the delamination in the work piece.

- The drill geometry and drill types also affect the machining quality, especially the delamination damage, to a great extent.
- It is not just the type of drill but the appropriate drill point geometry for a particular drill that helps in reducing the delamination.
- The material of drill also has a significant effect on drilling, as the tool-wear rate (TWR) is a function of drill material, thrust force is dependent of TWR and delamination is affected by thrust force.

To summarize, it could be mentioned that the machining quality while drilling a selected GFRP laminate could be improved by selecting the appropriate drill tool material bearing the required drill geometry, in addition to the optimum process parameters viz., speed and feed.

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